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Second-generation operational algorithm: Retrieval of aerosol properties over land from inversion of Moderate Resolution Imaging Spectroradiometer spectral reflectance

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[1] Since first light in early 2000, operational global quantitative retrievals of aerosol properties over land have been made from Moderate Resolution Imaging Spectroradiometer (MODIS) observed spectral reflectance. These products have been continuously evaluated and validated, and opportunities for improvements have been noted. We have replaced the surface reflectance assumptions, the set of aerosol model optical properties, and the aerosol lookup table (LUT). This second-generation operational algorithm performs a simultaneous inversion of two visible (0.47 and 0.66 μm) and one shortwave-IR (2.12 μm) channel, making use of the coarse aerosol information content contained in the 2.12 μm channel. Inversion of the three channels yields three nearly independent parameters, the aerosol optical depth (τ) at 0.55 μm, the nondust or fine weighting (η), and the surface reflectance at 2.12 μm. Retrievals of small-magnitude negative τ values (down to -0.05) are considered valid, thus balancing the statistics of τ in near zero τ conditions. Preliminary validation of this algorithm shows much improved retrievals of τ, where the MODIS/Aerosol Robotic Network τ (at 0.55 μm) regression has an equation of: y = 1.01x + 0.03, R = 0.90. Global mean τ for the test bed is reduced from ~0.28 to ~0.21.

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1. Introduction

[2] Aerosols are major players in Earth's climate, radiation budget, and cloud processes, and increasingly sophisticated and accurate remote sensing techniques have been introduced to characterize aerosols and their effects. Especially for aerosols over land, the first operational global satellite dataset has been provided by the Moderate Resolution Imaging Spectroradiometer (MODIS). Since MODIS' launch aboard *Terra* (in late 1999) and aboard *Aqua* (in early 2002), the use of the MODIS aerosol products has grown exponentially. Since launch, MODIS data and specifically aerosol data have been used to answer scientific questions about radiation and climate [e.g., *Intergovernmental Panel on Climate Change*, 2001; *Yu et al.*, 2006]. MODIS data are also being used for applications not previously considered, such as monitoring of surface air quality [e.g., *Chu et al.*, 2003; *Al-Saadi et al.*, 2005].

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[3] The MODIS instruments aboard Terra and Aqua both measure spectral radiance in 36 channels, in resolutions between 250 m and 1 km (at nadir). In polar orbit, approximately 700 km above the Earth, MODIS views a swath ~2300 km, resulting in near daily global coverage of Earth's land/ocean/atmosphere system. The swath is broken into 5-min "granules," each ~2030 km long. The operational algorithm over land uses MODIS reflectance data in three channels (0.47, 0.66, and 2.12 μm; bands 3, 1, and 7) to retrieve total spectral (function of wavelength, λ) "aerosol optical depth" (AOD or τ_λ) and "fine aerosol weighting" (FW or η). Additional channels are used to perform cloud masking and other decisions for pixel selection. The primary products (including τ and η) are reported at 10 km resolution (at nadir), at λ = 0.55 μm.

[4] *Kaufman et al.* [1997a] introduced the strategy for retrieving aerosol over land from MODIS. The top of the atmosphere reflectance ρ^* at a particular wavelength λ can be approximated by

$$\rho^*_\lambda(\theta_0,\theta,\phi) = \rho^a_\lambda(\theta_0,\theta,\phi) + \frac{F_\lambda(\theta_0)T_\lambda(\theta)\rho^s_\lambda(\theta_0,\theta,\phi)}{1-s_\lambda\rho^s_\lambda(\theta_0,\theta,\phi)} \quad (1)$$

where ρ^a_λ is the atmospheric "path reflectance," $F_{d\lambda}$ is the "normalized downward flux" for zero surface reflectance, T_λ represents "upward total transmission" into the satellite field of view, s_λ is the "atmospheric backscattering ratio," and ρ^s_λ is the angular "surface reflectance." These are in turn functions of solar zenith angle, satellite zenith angle, and solar/satellite relative azimuth angles (θ_0, θ, and φ, respectively). Except for the surface reflectance, each term on the right-hand side of equation (1) is a function of the Rayleigh scattering, aerosol type, and aerosol loading (τ). While equation (1) is technically valid for a uniform, Lambertian surface, the bidirectional properties of the surface reflectance can be approximated by the value of the surface reflectance for the relevant solar and satellite viewing geometry [*Kaufman et al.*, 1997a]. Assuming that a small set of aerosol types and loadings can describe the range of global aerosol, the algorithm relies on a lookup table (LUT) that contains precomputed simulations of these aerosol conditions. The goal of the algorithm is to examine the LUT to determine the conditions that best mimic the MODIS-observed spectral reflectance $\rho^m{}_\lambda$, and retrieve the associated aerosol properties (including τ and η). The difficulty lies in making the most appropriate assumptions about both the surface and atmospheric contributions.

[5] Since launch, the aerosol products have been monitored for quality, so the algorithm has been continuously improved and updated for bug fixes, cloud masking, and pixel selection. Updates to the operational algorithm are known as "versions," whereas products from particular processing periods are grouped into "collections." Details of a previous version (V4.2.2) and the products of "Collection 004" (C004) were described by *Remer et al.* [2005]. The second-generation algorithm described here and in the "Algorithm Theoretical Basis Document for Collection 5" (ATBD-2006; found online at http://modis-atmos.gsfc.nasa.gov/MOD04_L2/index.html), is known operationally as "V5.2" and is used for generated Collection 5 (C005) products. All updates to the operational algorithm can be found online at: http://modis-atmos.gsfc.nasa.gov/MOD04_L2/history.

[6] In order to justify the use of MODIS aerosol products for any application, the uncertainty of the retrieval must be quantified. Prior to launch, sensitivity tests and airborne simulations suggested that MODIS should be able to retrieve τ to within 20–30% (the expected error) over most vegetated and semivegetated land surfaces [e.g., *Kaufman et al.*, 1997a]. Since launch, validation studies suggested the expected error over land could be represented by

$$\Delta\tau = \pm 0.05 \pm 0.15\tau \tag{2}$$

[*Remer et al.*, 2005]. To this end, a number of papers attempted to "validate" the retrieved properties of C004 and before by comparing MODIS derived values to standard (ground truth) aerosol measurements, using the colocation method of *Ichoku et al.* [2002]. Ground-based Sun photometers, especially from the Aerosol Robotic Network (AERONET [*Holben et al.*, 1998]), have provided the bulk of the comparison data [e.g., *Chu et al.*, 2002; *Levy et al.*, 2005; *Remer et al.*, 2005]. Most of these validation studies have shown that although MODIS generally derived τ to within the expected error, MODIS tended to overestimate τ for small τ and underestimate for high τ [*Chu et al.*, 2002; *Remer et al.*, 2005; *Levy et al.*, 2005]. At 0.55 μm, we can consider a representative MODIS/AERONET regression of $\tau_{0.55}$ over land as

$$\tau_{\mathrm{MODIS}} = 0.1 + 0.9\,\tau_{\mathrm{AERONET}}. \tag{3}$$

[7] Any aerosol retrieval algorithm must make many assumptions about the complicated satellite signal. As a result of systematically evaluating key assumptions contained in the C004 algorithm family, we developed the second generation of operational MODIS retrieval over land (for processing C005). Section 2 introduces relevant C004 MODIS products and AERONET data used for development. Section 3 summarizes the aerosol optical models and the new LUT (described in a separate paper [*Levy et al.*, 2007]). Derivation of surface reflectance properties are discussed in section 4. Section 5 introduces a new retrieval methodology, and section 6 discusses the C005 products. Finally, we show provisional validation of the new algorithm in section 7.

8. Conclusion

[78] In this document, we have introduced a second-generation operational algorithm for deriving aerosol optical properties over dark land surfaces, from MODIS observed spectral reflectance. In the new algorithm, we have updated a number of assumptions, including the VISvs2.12 surface reflectance parameterization, and the statistical implications of deriving below zero aerosol optical thickness. Most significantly, instead of an independent two-channel retrieval, this new algorithm performs a simultaneous three-channel inversion to make use of aerosol information contained in the SWIR (2.12 μm) channel. We have coupled these changes with updated representative global aerosol optical models and lookup tables.

[79] This algorithm has been tested both for its theoretical ability to derive aerosol properties and on a test bed of 6300 MODIS granules. Compared with colocated AERONET sites, the new MODIS algorithm retrieves aerosol properties more accurately than the previous. Specifically, the retrievals of total τ meet expected accuracy levels ($\pm 0.05 \pm 0.15\,\tau$). MODIS/AERONET τ regression has an equation of: y = 1.01x + 0.03, R = 0.90. Global (the 6300 granules) mean τ has been reduced from 0.28 to 0.21. Retrievals of η show less significant improvement, but are still better correlated with AERONET results than previous versions. Retrievals of spectral Ångstrom Exponent show little or no improvement at this time. However, the new algorithm's derivation of fine τ ($\tau \times \eta$) is much improved. This product may be related to the anthropogenic contribution to the total τ [e.g., *Kaufman et al.*, 2005] and has specific applications for the climate community. Finally, the C005 products' quality assurance (QA) has been overhauled and is now more useful to users within the aerosol community.